RADAR SOUNDING STUDIES FOR QUANTIFYING REFLECTION AND SCATTERING AT TERRESTRIAL AIR-ICE AND ICE-OCEAN INTERFACES RELEVANT TO EUROPA'S ICY SHELL.

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Introduction: Jupiter's moon Europa is characterized by a pervasive icy mantle underlain by a global ocean. The distribution of free water and brines within Europa's icy/watery shell and the processes within the ice that control the exchange of material both with the surface and the ocean will determine Europa's suitability for harboring life. On Earth's ice sheets, radar sounding has proven to be a powerful tool for characterizing the ice-ocean interface as well as the overlying ice up to and including the air-ice interface. We present radar sounding techniques and new results from our recent airborne radar studies over ice-ocean environments in Antarctica.

Geologic Background: Certain processes hypothesized to occur for Europa's icy mantle and ocean have terrestrial analogs in the grounding zones of Antarctic ice streams [1-4]. These dynamic systems involve the interaction of the moving ice mass with the underlying materials, including liquid water (see Figure 1). Surface crevasses at varying levels accompany the ice streams due to high shear stresses at the ice stream margins. Bottom crevasses generally result at the grounding line due to tidal flexure. Once afloat, the ice and its interfaces continue to evolve. Ablation and accretion processes affect the character of the ice-ocean interface. Old bottom crevasses are healed, while new ones can be created, sometimes extending through the full ice thickness (see Figure 2). These processes continue beyond the calving of icebergs at the ice shelf front.

Imaging and characterizing the subglacial environment is fundamental to understanding these complex systems. Our focus has been to characterize the basal interface over the grounding zone of ice stream C and the ice-ocean interface of iceberg B-15 through radar reflection and scattering analyses. We also apply these techniques to the air-ice interface.

Echo Theory and Radar Methods: Echoes from the basal interface generally consist of both specularly reflected and diffusely scattered energy. Subglacial echoes are influenced by physical properties of the interface such as the composition, uniformity and roughness of the materials at the interface. Other important factors include dielectric losses and volumetric scattering losses from propagation through the ice as well as transmission at the air-ice interface. The primary physical factors influencing echoes from the air-ice interface are the surface roughness, the presence of surface crevasses, and the density of the air-ice mixture (firn).

Radar sounding techniques are well-suited to characterizing the reflection and scattering nature of both the ice-ocean and air-ice interfaces [5,6]. For example, unfocussed synthetic aperture radar (SAR) narrows the along-track radar beam, thus increasing resolution and the likelihood of specular reflection from the subglacial interface. Also, echo amplitude statistics can be used to identify reflecting or scattering regions. Fading analyses utilizing both echo amplitude and phase can provide estimates of the off-nadir extent of returned echoes, relating to scattering from the interface.

Radar System: Our radar system uses a programmable signal source with a dual-channel coherent down-conversion receiver [7] linked to a 10 kW transmitter. The radar operates in chirped pulse mode at 60 MHz and 15 MHz bandwidth. High and low-gain channels allow for recording both weak bed echoes and strong surface echoes simultaneously and without range-dependent gain control. Coherent data acquisition includes integrations of 16 returned radar signals about every 15 cm along-track. Pulse compression and unfocussed SAR processing using additional along-track integration were significant components of data analysis.

Results: Basal reflection coefficients are computed from these data and then used for inferring the subglacial materials, most notably regions where significant quantities of liquid water are present immediately beneath the ice. However, echo strength statistics based on reflection and scattering theory show that diffuse scattering can still dominate these echoes [8]. Scattering analysis includes imaging of the basal interface at short along-track integration distances to get a low resolution wide look at the basal interface. This is coupled with echo strength statistics (i.e., Rayleigh and Rice criteria) as well as echo amplitude and phase rates of change with distance (i.e., fading). Using the new radar data, we quantify off-nadir scattering from the subglacial interface to infer both the small-scale roughness and the distribution of slopes and facets associated with bottom crevasses and bedrock. We also identify and contrast regions of potential ablation and accretion at the ice-ocean interface.

A similar approach is applied to echoes from the ice-air interface. Reflection and scattering results show regions of heavy surface crevassing, as well as a variation in the surface reflection coefficient consistent with regional changes in firn density. We show that the level of crevassing is also well-quantified by off-nadir surface scattering and/or subsurface volume scattering.

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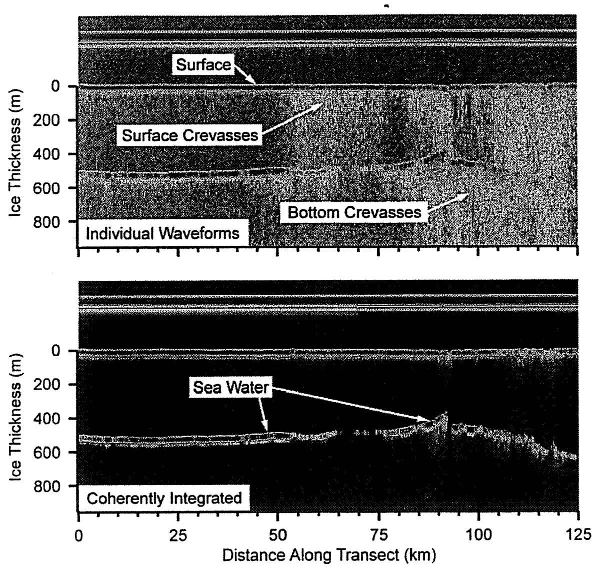

Figure 1. Coherent radar sounding profile at the grounding zone of ice stream C [5,6]. Individual waveforms (top panel) are coherently integrated along-track (bottom panel) implementing unfocussed SAR. Note the crevasse clutter cancellation. The labeled surface crevasses are the relict ice stream C shear margin. The bottom crevasses and overlying surface crevasses are due to tidal flexure at the grounding line.

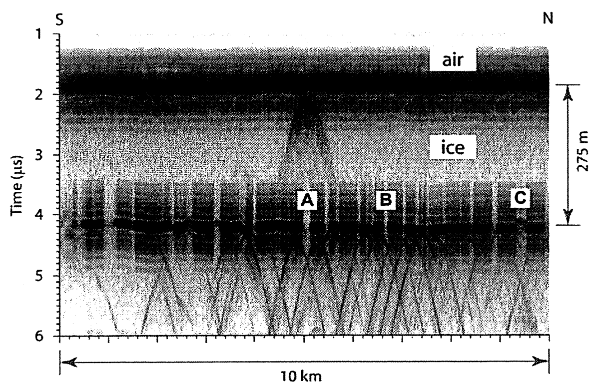

Figure 2. Radar sounding profile across a portion of iceberg B-15. Note the large crevasse (A) *extending through the entire ice thickness. Smaller bottom crevasses are also visible and are characterized by echoes up to 20 dB weaker than those for the adjacent ice-ocean interface.*